The anomalous properties of Markarian 1460

Neil Trentham[1], R. Brent Tully[2] and Marc A. W. Verheijen[3,4]

[1] *Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA.*
[2] *Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu HI 96822, U. S. A.*
[3] *NRAO-Array Operations Center, P. O. Box 0, Socorro NM 87801, U. S. A.*
[4] *Raman Research Institute, C.V. Raman Ave., Sadashivanagar, Bangalore 560 080, India*

1 February 2008

ABSTRACT

We present and discuss optical, near-infrared and HI measurements of the galaxy Markarian 1460 at a distance of 19 Mpc in the Ursa Major Cluster. This low-luminosity ($M_B = -14$) galaxy is unusual because (i) it is blue ($B - R = 0.8$) and has the spectrum of an HII galaxy, (ii) it has a light profile that is smooth and well fit by an $r^{1/4}$ and not an exponential function at all radii larger than the seeing, and (iii) it has an observed central brightness of about $\mu_B = 20$ mag arcsec^{-2}, intermediate between those of elliptical galaxies (on the bright μ_B side) and normal low-luminosity dwarf irregular (on the low μ_B side) galaxies. No other known galaxy exhibits all these properties in conjunction. On morphological grounds this galaxy looks like a normal distant luminous elliptical galaxy, since the fundamental plane tells us that higher luminosity normal elliptical galaxies tend to have lower surface-brightnesses. Markarian 1460 has 2×10^7 M$_\odot$ of HI and a ratio M(HI)/L$_B$ of 0.2, which is low compared to typical values for star-forming dwarf galaxies. From the high surface brightness and $r^{1/4}$ profile, we infer that the baryonic component of Markarian 1460 has become self-gravitating through dissipative processes. From the colours, radio continuum, HI and optical emission line properties, yet smooth texture, we infer that Markarian 1460 has had significant star formation as recently as ~ 1 Gyr ago but not today.

Key words: galaxies: individual: Markarian 1460 – galaxies: photometry – galaxies; clusters: individual: Ursa Major

1 INTRODUCTION

The global photometric properties of normal galaxies can be summarized by the following parameters: (1) absolute magnitude, (2) colours, (3) compactness, and (4) radial distribution and scale-length. To a first approximation, high-luminosity giant galaxies are either early-type (Elliptical or SO) and have a radial profile that is well-fit by a de Vaucouleurs (1948) $r^{1/4}$ law or late-type (spiral or irregular) and have a radial profile that is well-fit by an exponential law (Freeman 1970). Lower luminosity galaxies (dwarf irregulars and dwarf spheroidals) also have exponential light profiles (Binggeli & Cameron 1991) but have lower surface brightnesses. Many late-type galaxies have light profiles which can be decomposed into a bulge ($r^{1/4}$) and disk (exponential) part (Kormendy 1977, Kent 1985).

More subtle effects can be seen by examining correlations between the various parameters for a sample of galaxies (see Fig. 1):

(1) Early type galaxies are redder and have older stars than late-type ones.

(2) Luminous early-type galaxies tend to have higher surface-brightnesses than luminous late-type galaxies. They are more compact (there do exist, however, late-type galaxies with compact cores);

(3) Late-type galaxies tend to have lower surface-brightnesses as their luminosity decreases. This trend continues into the regime of dwarf galaxies;

(4) There is a tendency for more luminous early-type galaxies to have lower surface-brightnesses. This is characterized by the familiar fundamental plane for elliptical galaxies (Kormendy & Djorgovski 1989);

(5) Most low-luminosity galaxies tend to be late-type galaxies in the field and dwarf spheroidal galaxies in clusters;

There do exist other, rarer galaxies which are not well-described by the parameterizations used for normal galaxies. Examples are huge low surface-brightness giants like those studied by Sprayberry et al. (1995), peculiar interacting galaxy systems like Arp 220 (Sanders & Mirabel 1996), and blue compact dwarfs, low-luminosity galaxies which ap-
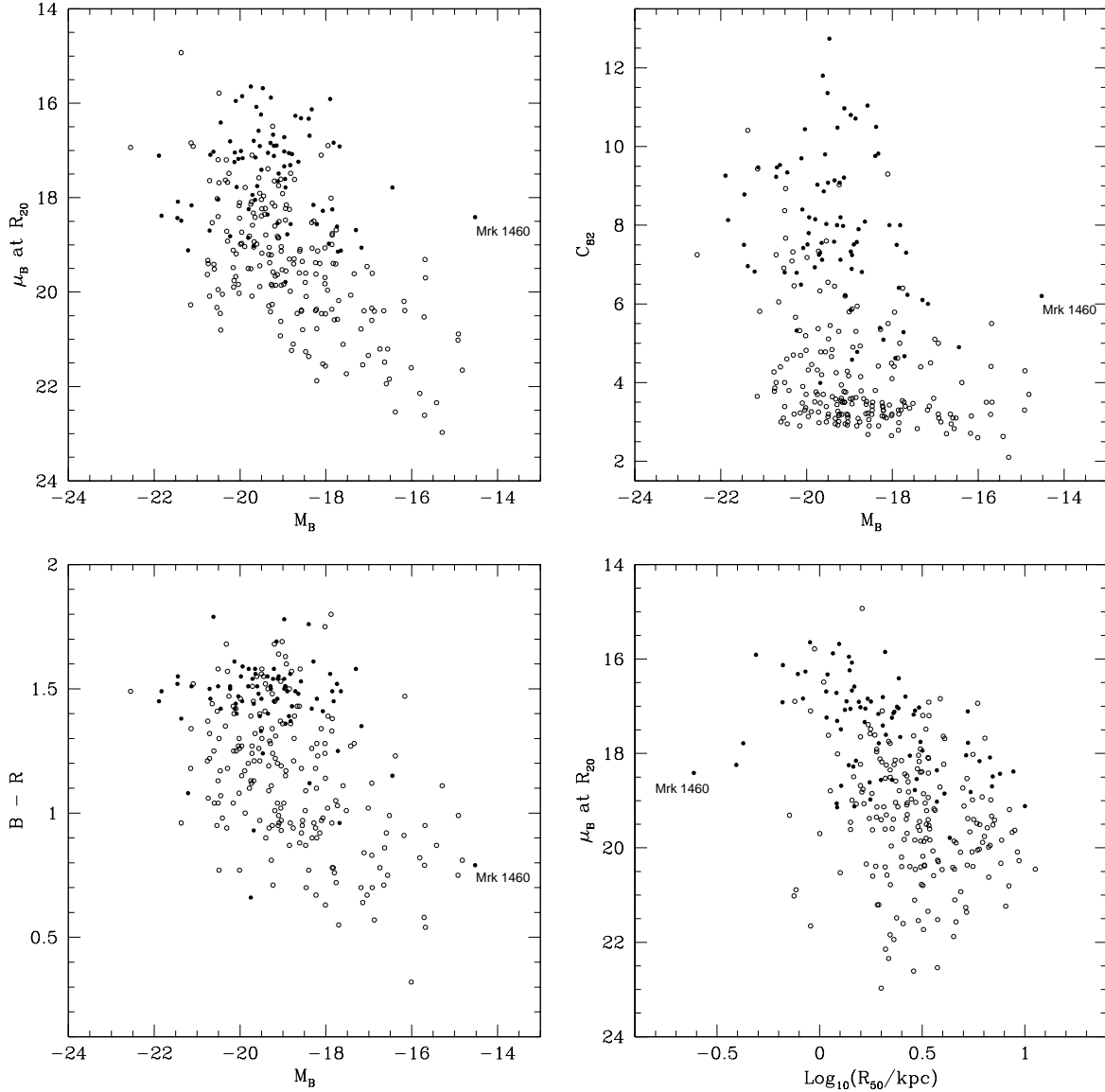
Figure 1. Photometric parameter correlations for early-type (filled circles; Hubble Type $T \leq 0$) and late-type (open circles; $T > 0$) galaxies from the samples of Pierce & Tully (2001; local field, Virgo and Fornax galaxies) and Tully et al. (1996; Ursa Major galaxies). The panels are: upper-left – absolute B magnitude M_B *vs.* effective surface brightness μ_B within an a radius R_{20} containing 20% of the light of the galaxy; upper-right – M_B *vs.* concentration index C_{82}, the ratio of the radii containing 80% and 20% of the total light; lower-left – M_B *vs.* $B - R$ colour; lower-right – half-light radii R_{50} *vs.* μ_B. Mrk 1460 is indicated in each panel and is classified as an elliptical galaxy by virtue of its $r^{1/4}$ profile (see the text) although its colours are more characteristic of late-type galaxies.

pear to have been caught in a short burst of extreme star formation.

We now present observations of another kind of galaxy that appears to be anomalous. It is Markarian 1460 (hereafter Mrk 1460), which is a low-luminosity ($M_B = -14.5$) blue emission-line galaxy with a $r^{1/4}$ light profile. This galaxy is anomalous since it looks morphologically like an elliptical galaxy and has no obvious sign of clumpiness (as do most blue emission-line low-luminosity galaxies which also have exponential light profiles; Telles, Melnick & Terlevich 1997). Its observed central surface-brightness is also much higher than that of most low-luminosity galaxies, about $\mu_R = 20$ mag arcsec^{-2}. This surface-brightness is characteristic of the most luminous elliptical galaxies. Mrk 1460 is,

however, much bluer than normal ellipticals. Mrk 1460 was identified in a spectroscopic survey of galaxies with ultraviolet continuum by Markarian et al. (1984), who showed that it was an HII galaxy in the Ursa Major Cluster of galaxies (distance modulus = 31.35; Tully & Pierce 2000). It was subsequently included in the photometric survey of the Ursa Major Cluster of Tully et al. (1996). Its compactness was noticed by Tully & Verheijen (1997) who classify it as a blue example of a compact dwarf ("Type 5" in their notation).

In Section 2 of this paper we describe the observations of this galaxy from our recent optical and HI surveys, and present the photometric properties in Section 3 and discuss them in the context of the radio and spectroscopic measurements. In Sections 4 through 6 we discuss similarities
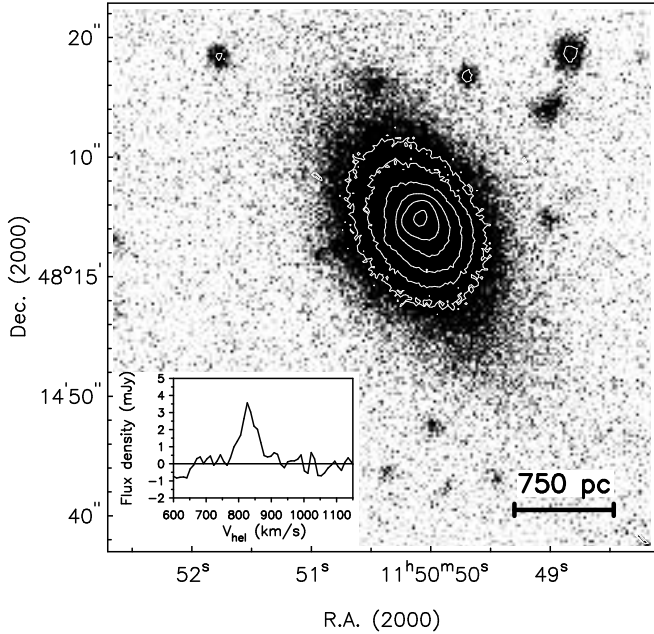
Figure 2. *R*-band image of Markarian 1460 from the data of Trentham et al. (2001). The insert is the HI spectrum from the data of Verheijen et al. (2001).

between Markarian 1460 and various other astronomical objects and possible formation scenarios.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Optical

In this work we use optical *BRI*-band images of Mrk 1460 from Tully et al. (1996) and deeper *R*-band data from Trentham, Tully & Verheijen (2001). The relevant telescopes and instruments, observing configurations, data-reduction strategies, and details of the photometric systems are given in those papers. The total magnitudes computed by Tully et al. (1996) are: $B = 16.89$, $R = 16.06$ and $I = 15.75$. These values have been updated to include Galactic extinction corrections from the data of Schlegel, Finkbeiner & Davis (1998) and do not include a correction for internal extinction. An *R*-band image of this galaxy is presented in Figure 2.

Old corrected apparent magnitudes : 16.83 16.04 15.73 (Table 5)

Of course, in the end it doesn't matter at all but you may want to drop the internal extinction correction and use the new Schlegel et al correction for Galactic extinction:

New Galactic extinction (Schlegel) : 0.09 0.06 0.04 New corrected apparent magnitudes : 16.89 16.06 15.75

2.2 Near Infrared

Mrk 1460 was imaged through a K' filter (Wainscoat & Cowie 1992) using the QUIRC 1024×1024 InSb array (Hodapp et al. 1996, scale $0.19''$ pixel^{-1}, field of view $3.2' \times 3.2'$) at the 2.24 m University of Hawaii Telescope on Mauna Kea on the night of January 23, 2000. Conditions were photometric for these observations with a median seeing of about

$0.7''$ FWHM. Exposures were as a sequence of five, one-minute frames, dithered in order to reject bad pixels. Offset fields were observed with equal exposure time to the target fields in order to perform a sky subtraction. Flat-field images were constructed using dome flats and sky images were constructed from the offset blank sky frames. Individual frames were flat-fielded, sky-subtracted, and then registered and combined. Instrumental magnitudes were computed from observations of $5 - 10$ UKIRT faint standards (Casali & Hawarden 1992), giving a photometric accuracy of about 2%. A 2σ isophotal magnitude from this image was measured as $K' = 14.92$. This will be somewhat fainter than the total magnitude since we are missing flux at large radii. If we estimate this flux from extrapolating the best-fit exponential light profile (as was done by Tully et al. 1996), the flux at large radius accounts for 0.58 magnitudes and the total magnitude is $K' = 14.34$. For the best-fitting $r^{1/4}$ light profile (see Section 3.1 and Figure 3 below), the flux at large radius accounts for 0.87 magnitudes and the total magnitude is $K' = 14.05$.

2.3 Radio

Mrk 1460 was observed with the VLA in its D-configuration by Verheijen et al. (2000, 2001) as part of a blind HI survey of the Ursa Major Cluster. The details of the observations are given there. The galaxy was detected in HI (see Fig.2 for the HI spectrum) and the observed width of the HI profile is 92 km s^{-1} at the 20% level. The total HI mass is 2×10^7 M$_\odot$ and the 1.4 GHz continuum flux density is 0.77 ± 0.43 mJy.

The emission is spatially unresolved given the $45''$ beam and it is unclear whether the width of the HI profile can be related to ordered rotation of a gas disk of unknown inclination in the gravitational potential of the galaxy. Consequently, estimating the dynamical mass from the width of the HI profile is not feasible. However, suppose the HI gas is distributed in a rotationally supported disk at an inclination of 60 degrees and that the maximum rotational velocity is reached at 1 kpc from the center which is roughly the observed optical extent. Correcting the width of the global HI profile for instrumental and turbulent broadening and inclination gives a rotational velocity of 41 km/s which translates to a total dynamical mass of 4×10^8 M$_\odot$ within a 1 kpc radius.

3 OBSERVED PROPERTIES OF MARKARIAN 1460

3.1 Light distribution

As mentioned in the previous section, Mrk 1460 appears on a CCD image similar to a distant elliptical galaxy by virtue of its $r^{1/4}$ light profile and its central surface brightness of about 19.5 R mag arcsec^{-2}, which is characteristic of the central surface-brightnesses of luminous elliptical galaxies. It is far more compact than any of the other dwarf irregular galaxies in the Ursa Major Cluster samples of Trentham et al. (2001) and Verheijen et al. (2001).

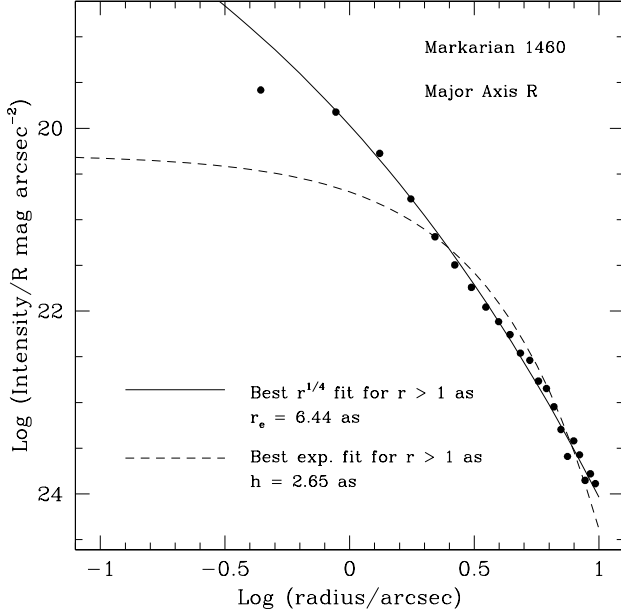The light profile is well fit by an $r^{1/4}$ profile (Fig. 3) in

Figure 3. The major-axis R-band light profile of Mrk 1460, from the data of Trentham et al. (2001). The filled circles represent the data. The solid line represents the best-fitting $r^{1/4}$ profile to the profile at radii greater than one arcsecond (the seeing FWHM). The dashed line represents the best-fitting exponential profile over the same radius range.

all passbands. It is smooth and only deviates from elliptical symmetry in the central 1.5 arcseconds; the flux peaks slightly to the northeast of the center as defined by the outer isophotes. Additionally, there is a modest and very low surface-brightness excess of light to the southwest. There is no sign of substantial clumpiness as is seen in the other low-luminosity galaxies in the Ursa Major sample of Trentham et al. (2001) with HI detections. An exponential law fails to fit the galaxy simultaneously at both small and large radii, at a high level of significance: the reduced χ^2 ($\nu = 10$ degrees of freedom) for the $r^{1/4}$ and exponential fits in Figure 3 are 0.85 and 131 respectively. The central surface-brightness derived from the $r^{1/4}$ fit at radii larger than one arcsecond (corresponding to the seeing radius) is $\mu_{0R} = 15.2$ mag arsec^{-2}. This extrapolated value is very much higher than the *measured* central surface brightnesses of about $\mu_{0R} = 19.5$ mag arsec^{-2}.

3.2 Current star-formation rate and metallicity

We can infer the star formation rate in Mrk 1460 from measurements of the OII line equivalent width (46 Å; Pustilnik et al. 1999) and also the 1.4 GHz continuum flux (Section 2.3, Verheijen et al. 2001). Both sets of measurements directly probe high-mass stars and their remnants and derivations of the star formation rate from these measurements therefore require very substantial corrections for low-mass stars, which dominate the total mass. Assuming a Salpeter (1955) stellar initial mass function and the OII line calibration of Gallego (1998), the current star formation rate in Markarian 1460 is $0.09\,\mathrm{M_\odot yr^{-1}}$. Assuming the same stellar initial mass function and the calibration of Cram et

al. (1998), the 3σ upper limit on the star formation rate derived from the 1.4 GHz measurements described in Section 2.3 is $0.11\,\mathrm{M_\odot yr^{-1}}$.

Deriving abundances from emission-line properties is complicated and a detailed analysis requires many more measurements than are available for this galaxy (Stasinska & Leitherer 1996). However, the following simple analysis is suggested. From the flux ratios O[II]/Hβ and O[III]/Hβ (Pustilnik et al. 1999), the abundance ratios O$^+$/H and O^{++}/H are 3.7×10^{-5} and 4.6×10^{-5}, leading to a value of the ionized gas oxygen abundance of O/H $= 8.3 \times 10^{-5}$. In this calculation we follow Tully et al. (1981) and adopt a normal Whitford (1958) reddening curve. If the heavy element abundance is proportional to the oxygen abundance, the total metallicity of the ionized gas in Mrk 1460 is then about 0.1 solar (Anders & Grevesse 1989).

3.3 Colours

The colours of this galaxy are: $B - R = 0.83$, $R - I = 0.31$, and $I - K' = 1.91$. The $I - K'$ colour is derived using aperture magnitudes within the K' 2-σ isophote; this ensures that we are measuring the same part of the galaxy in both filters and does not require us to make corrections for light lost below the sky at large radius in the K' image.

These optical colours suggest an age of approximately 1.3 Gyr if the galaxy has been forming stars either in an instantaneous burst at this time in the past or continuously with an exponential star-formation history profile with e-folding time 1 Gyr, given the models of Bruzual & Charlot (1993), assuming a Salpeter (1955) stellar initial mass function from 0.1 $\mathrm{M_\odot}$ to 100 $\mathrm{M_\odot}$), negligible internal extinction and a metallicity of 0.4 solar. The $I - K'$ colour above is, however, too red by about 0.7 magnitudes to be produced by the stars from this burst alone. This might suggest the presence of a population of older stars which only contribute in a small way to the optical fluxes. Probably the detailed star-formation history of this galaxy is too complex to derive from broadband colours alone, but it appears that a single recent star formation episode is unlikely since the optical–near infrared colour is so red. Indeed, the $B - K' = 3.1$ colour of this galaxy is redder than that of 31 of the 33 galaxies with Hubble Type $T \geq 6$ in the Ursa Major sample of Tully et al. (1996) that have near-infrared photometry, all of which have blue optical colours.

The colour gradients that we measure in this galaxy are fairly small: $\mathrm{d}(B - R)/\mathrm{d}r \approx 0.27\,\mathrm{mag\,arcsec^{-1}}$ between 1 and 2 arcsec and $\mathrm{d}(B - R)/\mathrm{d}r \approx 0.13\,\mathrm{mag\,arcsec^{-1}}$ between 2 and 4 arcsec (note that 12 arcsec corresponds to 1 kpc at the distance of this galaxy) along the major axis. The central colour that we measure within the seeing FWHM radius is $B - R \sim 0.5$, about 0.3 magnitudes bluer than for the galaxy as a whole. This might suggest that the stars in the very center of the galaxy are slightly younger than average stars in the galaxy (we will return to this point in Section 5).

3.4 Total baryonic content

The total B-band solar luminosity is $L_B = 1.0 \times 10^8 \mathrm{L_{\odot B}}$, and the HI gas mass is $M(\mathrm{HI}) = 2 \times 10^7\,\mathrm{M_\odot}$. The ratio

$M(\mathrm{HI})/L_B$ is then 0.2, which is lower than the values normally seen for very late-type emission-line galaxies (Young & Knezek 1989, Verheijen & Sancisi 2001). It therefore appears that Mrk 1460 is deficient in HI for a normal star-forming dwarf galaxy.

Given the star-formation rate and age in the previous two sections, the total stellar mass of Mrk 1460 is $7\times10^7\,\mathrm{M_\odot}$. This suggests that the HI gas only contributes about 20 per cent of the total baryonic mass. This last number depends on both the shape of the stellar initial mass function at low masses and on the normalization of Gallego's (1998) calibration, both of which are very uncertain. However the low value of $M(\mathrm{HI})/L_B$ does suggest that the baryonic mass of Mrk 1460 is not heavily dominated by cold atomic gas.

The total baryonic mass is then about $7\times10^7\,\mathrm{M_\odot}$ (the mass in stars) plus $2\times10^7\,\mathrm{M_\odot}$ (the mass in HI) plus $7\times10^7\,\mathrm{M_\odot}$ (accounting for the helium mass fraction in the cold gas), totalling $1\times10^8\,\mathrm{M_\odot}$. This is comparable to the dynamical mass estimated in Section 2.3, which suggests that the baryons are self-gravitating, at least in the center of the galaxy.

4 DISCUSSION

In this section we discuss similarities and differences between Markarian 1460 and other low-luminosity galaxies. We then argue that galaxies like this are rare and suggest possible reasons for why it is so different to the majority of low-luminosity galaxies.

Low luminosity galaxies can be discussed in the context of their surface brightness and age properties.
(i) Tully & Verheijen (1997) have suggested that the separate regimes of low and high surface brightness can be distinguished on the basis of dynamical evidence as follows. In low surface-brightness systems the observed baryonic component cannot account for the observed rotation with reasonable mass-to-light choices and it is inferred that dark matter is dynamically dominant even near the galaxy centers. In high surface brightness systems the observed light and a reasonable association of mass-to-light comfortably accounts for the inner galaxy rotation and it can be concluded that the baryonic component is self-gravitating within the inner couple of exponential scalelengths;
(ii) Systems with young populations still have cold gas and are still forming stars or have only just recently completed a major episode of star formation. They are blue, gas-rich and tend to have clumpy light distributions. Systems with only old populations do not have a gas reservoir and the old stars have little or no memory of the precise location of their birthplaces due to stellar-dynamical effects like phase mixing and violent relaxation.

Most low-luminosity systems with young populations are dwarf irregular galaxies, which are low surface-brightness systems. A detailed study of the morphologies of low-luminosity star-forming galaxies is performed by Telles et al. (1997). They found that the majority of their sample galaxies had azimuthally-averaged exponential light profiles (see their Section 3.5). This was also true of all the other galaxies in the Ursa Major sample of Trentham et al. (2001). Most of the star-forming galaxies in both the Telles et

al. sample and in the Ursa Major sample also showed evidence for lumpy, irregular morphologies.

Low suface-brightness galaxies with only old stars are dwarf spheroidal galaxies, which are red, gas-poor, and have smooth light profiles that are also exponential. This is the type that is so numerous at faint magnitudes in the Virgo (Phillipps et al. 1998) and Fornax (Kambas et al. 2000) Clusters. The similarity in profile shapes and surface brightnesses (Binggeli & Cameron 1991, Binggeli 1994) between dwarf irregular and spheroidal galaxies is suggestive of an evolutionary link: for example, dwarf spheroidals may be dwarf irregulars that have blown out any residual gas via supernova-driven winds at some time in the distant past (e.g. Kormendy & Bender 1994).

Red compact dwarfs are also gas-poor and consist of old stars, but these have high surface-brightnesses. These normally have $r^{1/4}$ light profiles. The scatter in central surface-brightness of such objects is large, ranging from about 13 B mag arcsec^{-2} for M32 (Binggeli & Cameron 1991) to about 19 B mag arcsec^{-2} for UGC 6805 in the Ursa Major Cluster (Tully et al. 1996).

Markarian 1460 is the rare example of a high surface-brightness galaxy caught in transition *between young and old*. Like red compact dwarfs, it has a smooth $r^{1/4}$ light profile. Its central surface-brightness of 20.7 B mag arcsec^{-2} is at the faint end of the range of central surface-brightnesses for elliptical galaxies and red compact dwarfs, hence its appearance similar to that of a distant luminous elliptical galaxy (consider just the filled circles in the upper left panel of Fig. 1). Like dwarf irregular galaxies, Mrk 1460 has young stars and an emission-line spectrum (Pustilnik et al. 1999). Blue compact dwarf (BCD) galaxies with $r^{1/4}$ light profiles have been known to exist for some time (e.g. Kunth, Maurogodarto & Vigroux 1988). Doublier (1998) places a number of these objects on a magnitude vs. central surface-brightness plot, and finds that they lie close to the highest surface-brightness red compact dwarfs like M32, several mag arcsec^{-2} brighter than Mrk 1460. A well-studied example is NGC 1510 (Disney & Pottasch 1977, Kinman 1978), which also shows strong emission lines. Unlike Mrk 1460, however, this galaxy exhibits considerable clumpiness (Eichendorf & Nieto 1984). More generally, BCDs possess localized regions undergoing intense star formation burst where the surface brightnesses is extremely high. In Mrk 1460, however, the young stars exist on a galactic scale and are not just restricted to any particular star-forming region.

Galaxies with the properties of Mrk 1460 have not turned up in field optical spectroscopic (e.g. Ellis et al. 1996, Lin et al. 1996) or HI (e.g. Zwaan 1998) surveys (however see Drinkwater et al. 1988 for some possible counterparts in the Fornax Cluster). They are presumably very rare. This is not surprising, since the current star-formation rate of 0.1 $\mathrm{M_\odot\,yr^{-1}}$ exhausts the HI gas in 2×10^8 yr, which is small compared to a Hubble time. It is likely that Mrk 1460 will evolve into an old high surface-brightness dwarf, albeit one at least two magnitudes fainter than UGC 6805 once fading is taken into account (this would be the lowest luminosity $r^{1/4}$ galaxy known). Its final surface brightness will probably be close to what it is now: Mrk 1460 does not possess enough cold gas (unless it is in molecular form, but there is no *IRAS* detection at this position) to convert to stars via an extreme dissipative collapse, which is what would be

required were Mrk 1460 to turn into a very high surface-brightness red compact dwarf like M32.

So what happened to cause this galaxy to have these anomalous properties? Making $r^{\frac{1}{4}}$ galaxies by violent relaxation on timescales short compared to stellar population evolutionary timescales does not seem to be a problem (Lynden-Bell 1967, van Albada 1982). However, why this happened in this particular case, and not in most low-luminosity star-forming galaxies (which have exponential profiles and lower surface brightnesses) is unclear. It might be an environmental effect: Tully & Verheijen (1997) suggest that tidal interactions can radially scramble the baryonic mass, presumably through gas collisions. The baryonic matter transferred inward during an encounter with another galaxy can become sufficiently concentrated that it becomes self-gravitating. A self-gravitating disk will then further rearrange itself into a radially stable configuration (Mestel 1963). The result is a high concentration of baryons towards the center of the galaxy, which in turn leads to the high surface brightness relative to what is seen in most low-luminosity galaxies. A related possibility is that Mrk 1460 formed out of a dense, self-gravitating gas cloud assembled via a hydrodynamic shock process (Barnes & Hernquist 1992), perhaps in proximity to another galaxy in the Ursa Major Cluster.

More generally, understanding the physical mechanisms at work would be helped significantly by obtaining a sample of objects like Mrk 1460. Such galaxies are distinctive in spectroscopic surveys since their surface brightnesses are high and their emission lines are strong. This will shortly be possible as large samples of galaxies with known redshifts and morphological information become available from the new generation of wide-field deep redshift surveys like the Sloan Digital Sky Survey and the 2DF Survey.

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